SPIRAL at GANIL: Latest Results and Plans for the Future

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[a]GANIL (IN2P3/CNRS - DSM/CEA) B.P. 55027 14076 Caen Cedex 5, France

[b]LPC - ENSICAEN , 6 bd. Maréchal Juin 14050 Caen Cedex, France

[c]CIRIL - ENSICAEN , 6 bd. Maréchal Juin 14050 Caen Cedex, France

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The first accelerated exotic beam of the SPIRAL (Production System of Radioactive Ion and Acceleration On-Line) facility at GANIL at Caen has been delivered for experiments in September 2001. After working for almost 5 years, 32 experiments were performed in the facility using exotic isotopes of helium, oxygen, neon, argon and krypton. The intensities of the radioactive beams increased since the first beam was delivered. Nominal intensity values are achieved for most of noble gas beams. Developments of new beams as well as the increasing of present intensities for a number of isotopes are being undertaken. In particular, in this contribution it is presented the first results obtained for the production of light alkali beams. Other developments are also envisaged in the close future.

1. INTRODUCTION

The use of high-energy fragmentation as well as the ISOL (Isotopic Separation On-Line) methods for exploring the structure of nuclei far from stability became one of the major activities at GANIL (Grand Accélérateur National dIons Lourds), the first operational high intensity heavy ion accelerator in the 50-100 MeV/nucleon domain. It turns out from the principle of production and separation using a spectrograph, the so-called in-flight method [1], that the optimum efficiency of the process is reached when the radioactive beam has a velocity similar to that of the primary beam. This production process, however, does imply losses in intensity and/or quality of the secondary beam, which becomes increasingly important as the beam is slowed down. The ISOL (Isotopic Separation On-Line) method, used at SPIRAL [2], provides for production and separation of radioactive ion beams, with subsequent acceleration by a K=265 cyclotron (CIME, Cyclotron d' Ions à Moyenne Energie) between 1.7 and 25A MeV. This opened up the possibility to study nuclear reactions around and slightly above the Coulomb barrier with radioactive ion beams at GANIL. In brief, the general scheme of the SPIRAL project is the following: the series of the three GANIL cyclotrons is used as a driver which bombards a production target placed in a heavily shielded cave located beneath ground level in the accelerator building (Figure 1).

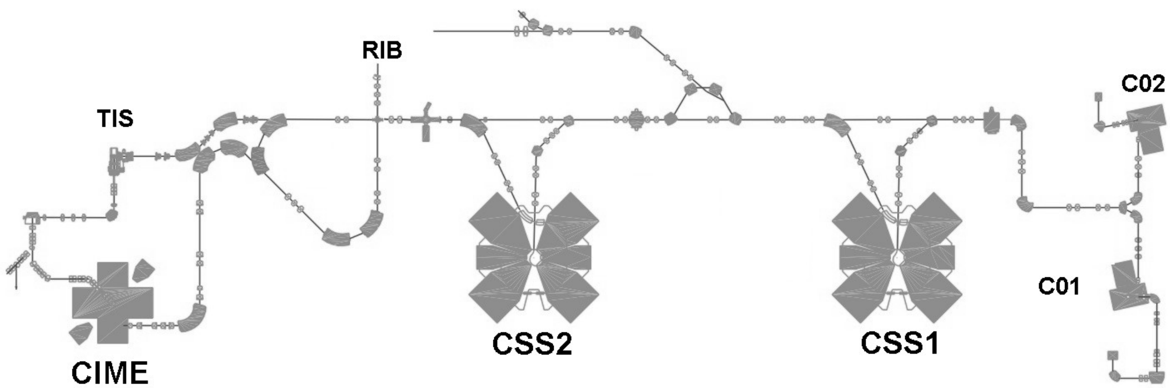

Figure 1. GANIL and SPIRAL acceleration system. C01 and C02 are the injector cyclotrons. CSS1 and CSS2 are the separated sector cyclotrons. TIS is the target ion source production system of SPIRAL. CIME is the radioactive beam cyclotron. Radioactive ion beams (RIB) are delivered after selection by the alpha-shaped spectrometer.

In addition to the target-ion source system, both high and low-energy "front-ends" are installed in the cave. The exotic nuclei produced by nuclear reactions are released from the high temperature target (2000^{o}C), then pass through a cold transfer tube into an ECRIS source where they are ionized up to a charge-to-mass ratio larger than 1/11. After extraction from the ECRIS with an acceleration voltage up to 36 kV, the low-energy beam is selected by a relatively low-resolution separator ($m/\Delta m = 250$) and injected into CIME. The exotic beams can be accelerated in an energy range of 1.7A MeV to 25A MeV and, after extraction, the proper magnetic rigidity is selected by the modified alpha spectrometer of GANIL and directed to one of the existing experimental caves. The mass separation is performed for the most part by the cyclotron itself with a resolving power of more than $2,500$. An additional separation can be achieved by stripping at the object point of the spectrometer in order to select ions having the same charge-to-mass ratio but different masses, or by using a degrader to select the isobars. However, an intensity loss is the price to be paid for either of these two methods.

2. TARGET-ION SOURCE PRODUCTION SYSTEM

In the classic ISOL technique a proton or a light-ion beam is accelerated to a high energy and bombards a thick target, producing radioactive nuclei by spallation reactions, fragmentation of the target and/or induced fission. Other reaction mechanisms, however, come into play with heavy ions. In particular, projectile fragmentation is the process of most importance. In all cases, the fragments are stopped in the target, which is heated to a high temperature to facilitate the migration of the radioactive atoms to the surface. Usually the target is located at a short distance from the ion source and the radioactive atoms effuse via a transfer tube to the plasma region where they are ionized and then accelerated. As the atoms are ionized and accelerated in a manner identical to that for stable beams, the resulting radioactive beams have good dynamical and optical characteristics when compared with projectile fragmentation, as well as an energy, which may be precisely adjusted. The originality of the GANIL project lies in the use of an extended range of heavy ions, up to the maximum available energies. Such an approach differs from the proton (or light-ion) beam technique in that the projectile rather than the target is varied in order to produce the different radioactive species, thereby allowing the use of the most resilient and efficient production target for most cases. For SPIRAL, the high-energy beam delivered by the present GANIL cyclotrons interacts with a thick target, where all the reaction products are stopped. The target is thereby heated by the primary beam up to 2000^{o}C. Such a temperature is a challenge for the target in terms of reliability and duration. A numerical code has been developed to simulate the temperature distribution inside the target and is described in [3]. It can be shown with this code that convenient temperatures (about 2000^{o}C) can be achieved with high primary beam powers if the target presents a conical shape. In the case of a low power primary beam, extra ohmic heating can be added through the axis of the target to maintain the diffusion of the exotic ion beam.

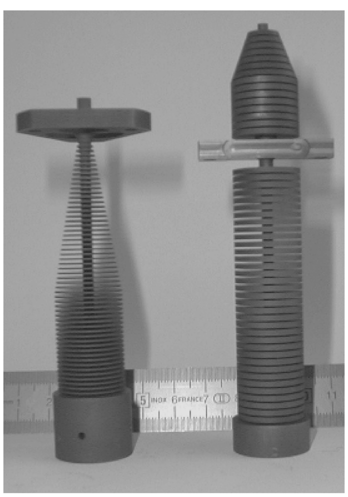

Figure 2. SPIRAL graphite targets. The right one is specially designed for production of He isotopes (see text). The pictures correspond to targets for maximum beam power of 1,500W.

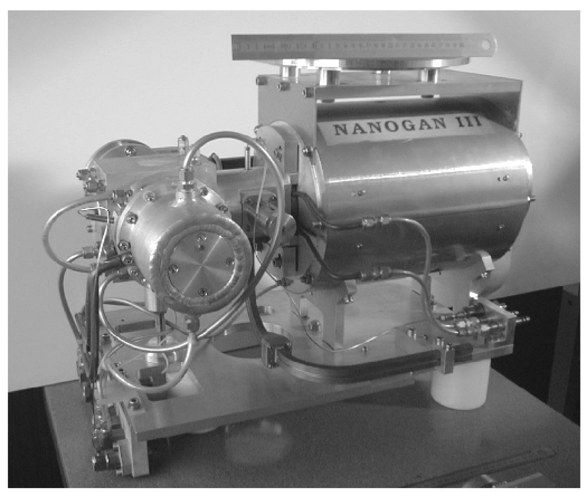

Figure 3. SPIRAL target ion source ensemble. The ECRIS NANOGAN-3 as well as the target container are mounted in a support plate, which can be remotely removed from the production cave.

After production and diffusion, the radioactive atoms effuse to the ion source through a cold transfer tube that makes a chemical selection, as the main part of the non-gaseous elements sticks on the walls of the tube. The atoms then enter into the ECR (Electron Cyclotron Resonance) ion source Nanogan-3 [4] where they are ionized and extracted to form the radioactive ion beam. The number of radioactive atoms created by this method depends on the primary beam intensity, which has been recently upgraded [5], and on the integrated fragmentation cross section. However the creation rate of nuclei of interest is always low, and the major problem of the method is to be as efficient as possible in order to maintain suitable radioactive ion beam intensity. This means that the system of production of the radioactive ion beam has to take into account all the loss processes that can occur, like sticking on the walls, leaks, chemical reactions, etc. The production time, including diffusion out of the target, effusion, ionisation and confinement, has to be compatible with the life-time of the nuclei of interest. In order to test the properties of the target ion source (TIS) systems, the separator SIRa (limited to 400W of primary beam power) was built in 1993. It allowed the test of different configurations of production systems under real conditions [6],[7],[8],[9]. The present Nanogan-3 configuration is composed of a graphite target (Figure 2) with a microstructure with 1μm grain size, coupled to a 10 GHz permanent-magnet ECR (Figure 3) ion source via a cold transfer tube. This configuration is mainly dedicated to gaseous elements that do not stick on the walls.

Particularly for ^{6}He and ^{8}He, a special target has been developed which is divided into two parts because of the long range of He in carbon. The first part, the production target, induces fragmentation of the carbon primary beam and also fragmentation of carbon atoms of the target. Helium produced by projectile fragmentation stops in the second part of the target (the diffusion target) while the He produced by target fragmentation stops in the production target. The carbon ions of the primary beam that do not react are also stopped in this first part. By this means, the production target is heated by the primary beam power, allowing the diffusion of the He atoms produced by the fragmentation of the carbon atoms of the target, while the diffusion target needs ohmic heating to reach a suitable temperature for diffusion. Radioactive oxygen beams have been produced by using the fact that a radioactive oxygen atom produced in the graphite target can combine with the carbon and produce a CO molecule that diffuses to the ion source. The behaviour of the ion source has also been studied by comparing the charge state distribution of multi-charged ions during different moments of the production. It was observed that after a short delay of out-gassing, the source behaviour is no longer affected by the presence of the target in its neighbourhood. As expected, the charge state distribution of radioactive noble gases does not show any difference from that of stable isotopes. Radiation risks, choice of materials and the reliability of the radioactive ion beam production system have been taken into account in the design of the production cave. As a consequence, primary beams impinging on the SPIRAL targets are limited to an intensity of 2 10^{13} pps or 6 kW of beam power.

3. RADIOACTIVE BEAM INTENSITIES AND RELIABILITY

The intensities of all possible beams available at SPIRAL are permanently updated in the GANIL web-page [10]. In all cases, off-line reliability tests have been successfully performed over a long period (more than 20 full days). On-line tests show that the targets can work for at least 15 days without damage. A list of beams presently provided at SPIRAL is shown in Table 1.

The number of 32 experiments were performed at SPIRAL up to July 2006, using 24 TIS. This corresponds to more than 8,000 hours of beam on the production target. The average ratio between the total beam time scheduled and the beam time actually furnished to the experiments is about 85 %. Three experiments could not be done due to breaking of the production system. Two of them were already re-scheduled. Both experiments successfully obtained data.

The overall efficiency of the system varies with the lifetime of the isotope and the extraction voltage of the TIS. Typical efficiencies obtained are of the order of 50%, for diffusion/effusion for atoms of ^{6}He ($T_{1/2} = 0.8$ s) and of 20% for transport and acceleration at extraction voltages around 20 kV. Typical ionization efficiencies are of 90% for 1^{+} and of the order of 7% for 2^{+} charge states.

The extraction voltage is tuned depending on the required post-accelerated beam energy.

After the year 2003 a new target for He beams was developed, for use with 3.0 kW beam, corresponding to the maximum ^{13}C beam intensity available at GANIL. This intensity allows to obtain the beam intensities for ^{6,8}He shown in Table 2.

Table 1
List of presently available beams at SPIRAL.

Element	A									
Kr	72	73	74	75	76	77	79	81		
Ar	31	32	33	34	35	41	42	43	44	45	46
Ne	17	18	19	23	24	25	26	27		
F	18									
O	14	15	19	20	21	22				
N	13	16								
He	6	8								

The experimental beam intensities are given in ref. [10].

Table 2
Measured radioactive beam intensities for He isotopes corresponding to a primary beam power of 2.5 kW. The quoted numbers were not measured at same extraction conditions.

Beam	Charge	Low Energy Yield (pps)	Accelerated Yield (pps)	Min. Energy (A MeV)	Max. Energy (A MeV)
^{6}He	1+	$2\ 10^{8}$	$2.8\ 10^{7}$	3.2	7.3
^{6}He	2+	$1\ 10^{7}$	$5\ 10^{6}$	-	20
^{8}He	1+	$1.3\ 10^{6}$	$1.8\ 10^{5}$	3.8	4.1
^{8}He	2+	$6.5\ 10^{4}$	$5\ 10^{4}$	-	15.4

4. NEW DEVELOPMENTS

Alkali beams are being developed for SPIRAL. The production principle is based on projectile fragmentation in a graphite target. The target has approximately the same design as the previous one, for gaseous elements and compounds. The difference from the previous design is that a surface ionization ion source is coupled directly to the target and serves for the production of 1^+ ions immediately after the radioactive atoms diffusion out of the target. The ion source is constituted by a carbon tube of 2 cm long and 4 mm diameter, heated independently from the target. After first ionization, the 1^+ beam is accelerated and directed to the NANOGAN-3 ECRIS. The 1^+ beam is afterwards decelerated to very low energy (of the order of 5 eV) in order to be injected into the ECR plasma of the ECRIS. After that, the beam will be extracted as multi-charged ions from the ECRIS and conducted to CIME for further acceleration. In this process no heating of the transfer tube between the target container and the ion source, as well as the ion source chamber, is needed. Alkali elements are easily ionized by surface ionization ion sources with excellent efficiencies and we estimated that the injection of the 1^+ beams can also be implemented with efficiencies of the order of 50%, which would give reasonable performances for the overall production system.

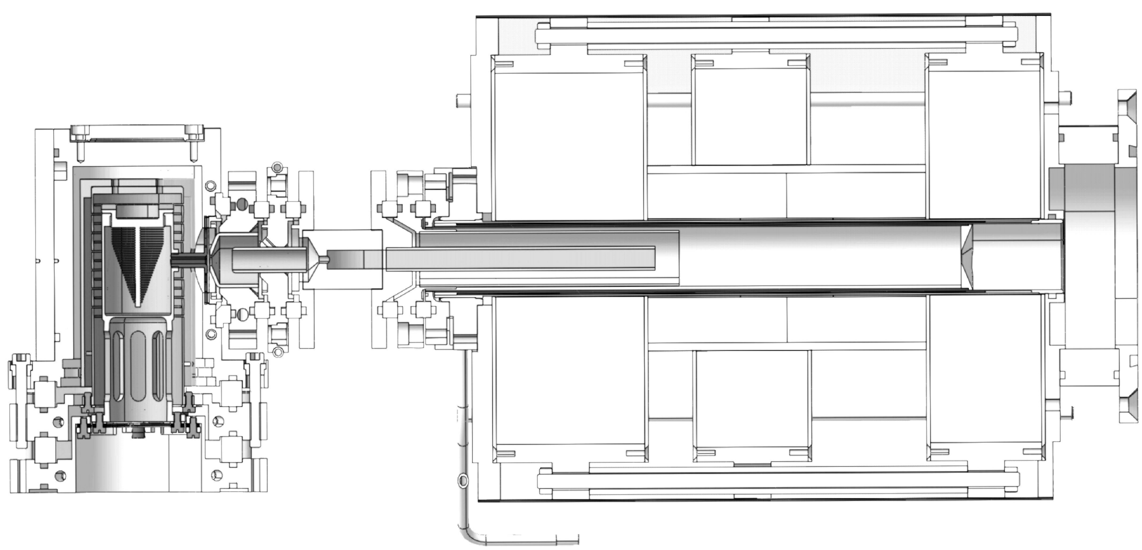

Figure 4. TIS for production of alkali at SPIRAL. In the left side a target is embedded in a surface ionization ion source. The ECRIS represented on the right is the fully permanent magnet NANOGAN-3.

It should be noted that in any case, due to the high ECR plasma potential energy, any ion can only be injected in the ECR plasma if it has sufficient energy to overcome this barrier. Therefore, a fine tuning is needed for injecting 1^+ beams into the ECR plasma.

Table 3
Measured radioactive beam intensities for 1^+ alkali isotopes using ^{48}Ca primary beam at 60A MeV with intensity normalized to 0.14 pμA (400W).

Beam	Lifetime (s)	Yield (pps)	Efficiency (%)
^{8}Li	0.84	$1\ 10^6$	13
^{9}Li	0.18	$3.4\ 10^4$	2.1
^{25}Na	59.1	$3\ 10^7$	34
^{26}Na	1.07	$6.5\ 10^6$	18
^{27}Na	0.30	$9.5\ 10^5$	10
^{29}Al	394	$1.8\ 10^6$	1.2
^{37}K	1.2	$7.5\ 10^4$	31
^{47}K	17.5	$1.8\ 10^8$	42

That is also the reason why a simple transfer of alkalis via a hot surface tube would not work: ions, which would be surface ionized along the path between the target and the ECRIS, would not be able to overcome the plasma barrier. Figure 4 shows the new TIS system and the short optical beam transfer between the 1^+ and the ECR ion sources.

Preliminary tests of the surface ionization ion source (the left part of Figure 4) were performed at SIRa test bench using ^{48}Ca primary beam at 60A MeV with intensity of 70 pnA. Table 3 present the obtained yields as well as the overall efficiencies for Li, Na and K isotopes.

The efficiencies obtained are in good agreement with estimated diffusion/effusion and ionization using a carbon ionizer. Tests of the overall system, including injection and extraction of the beam in NANOGAN-3 will be performed in spring 2007. Alkali beams will be available at SPIRAL in 2008.

5. SUMMARY

SPIRAL (Production System of Radioactive Ion and Acceleration On-Line) facility at GANIL at Caen has delivered its first beam in September 2001. After working for almost 5 years, 32 experiments were performed in the facility using exotic isotopes of helium, oxygen, neon, argon and krypton. The intensities of the radioactive beams increased since the first beam was delivered. Nominal intensity values are achieved for most of noble gas beams. Developments of new beams as well as the increasing of present intensities for a number of isotopes are being undertaken. Promising efficiencies were obtained for the production of Li, Na, K as well as Al isotopes with a new surface ionization ion source, which will be in the future coupled with the present ECRIS NANOGAN-3.

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